# Optimizing Boosted Dark Matter Searches at Large-Mass Neutrino and Dark Matter Detectors

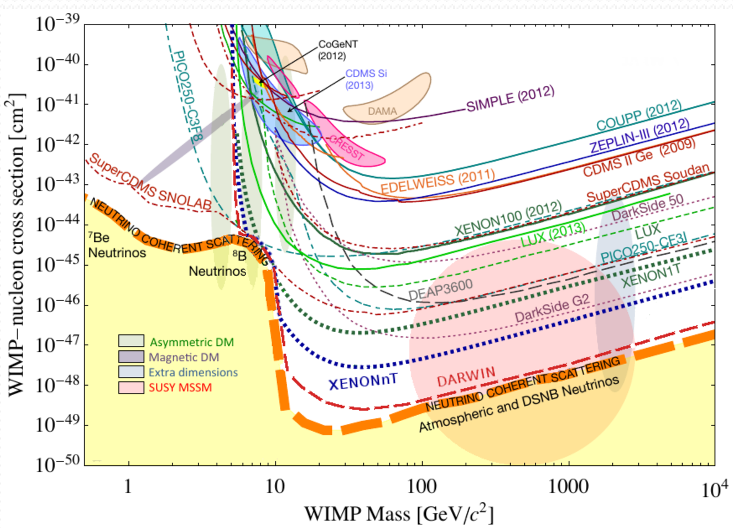
**Doojin Kim**

NuTheories Workshop by PITT PACC, November 6th, 2018

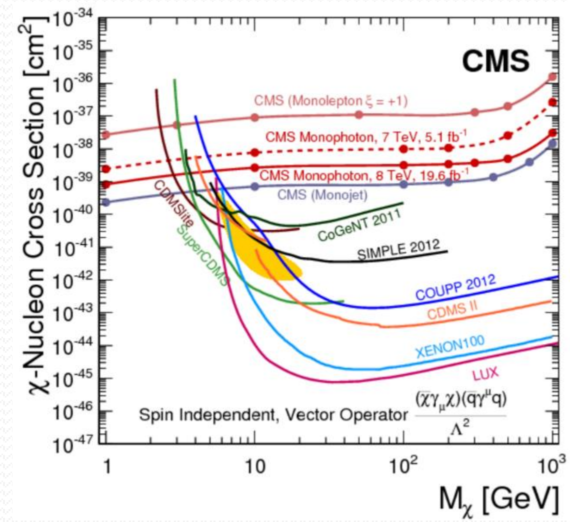
In collaboration with Pedro Machado, Jong-Chul Park and Seodong Shin, in progress

# Nonrelativistic Dark Matter Searches

- **No observation** of DM signatures via non-gravitational interactions while many searches/interpretations designed/performed under nonrelativistic WIMP/WIMP-like scenarios ⇒ merely excluding more parameter space in dark matter models




[Cushman, Calbiati, McKinsey (2013); Baudis (2014)]

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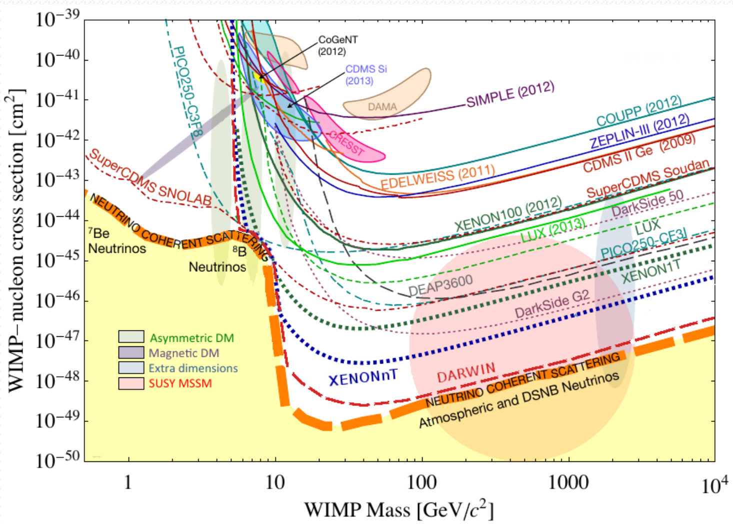


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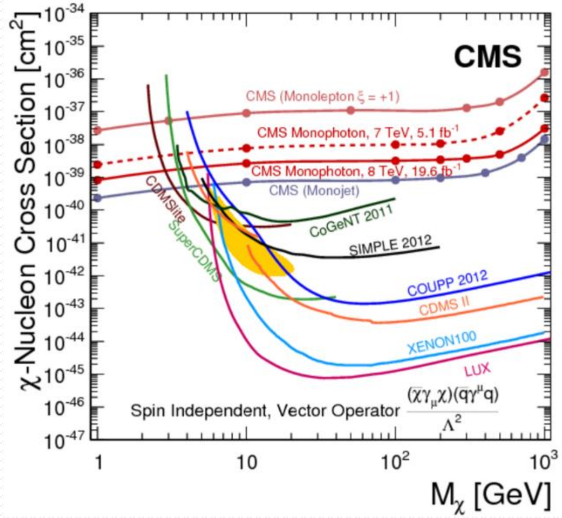


[CMS mono-photon search (2014)]

*Time to change our approach?*

⇒ *Relativistically produced invisible particle (DM) search!* (see Josh's talk)

# Boosted/Relativistic Dark Matter: Intensity Frontier

- Signals coming from particle accelerators, additional model building not always necessary
- If dark sectors (containing dark matter) are more "weakly" connected to the SM sector, high intensity experiments are motivated, e.g., fixed target experiments.
  - ✓ BDX, NA64, MicroBooNE, SeaQuest, LDMX, T2HKK, DUNE, SHiP, and many more

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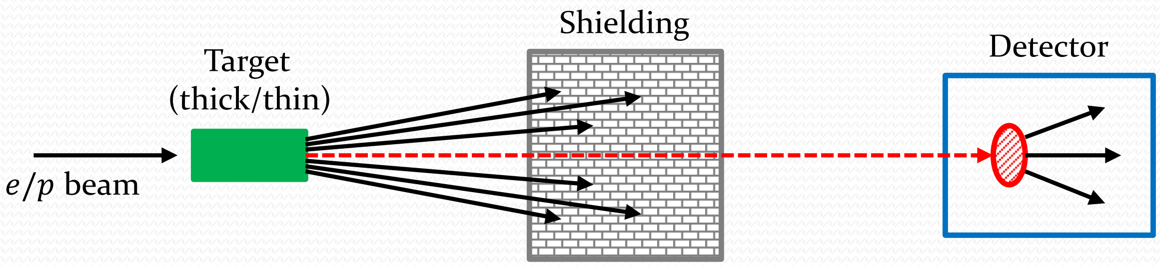

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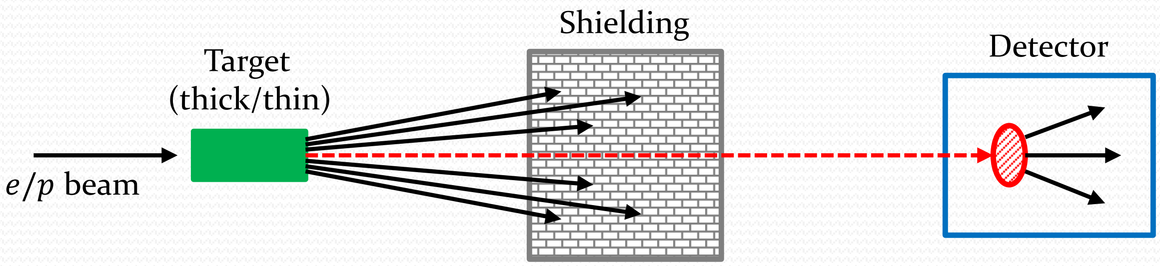
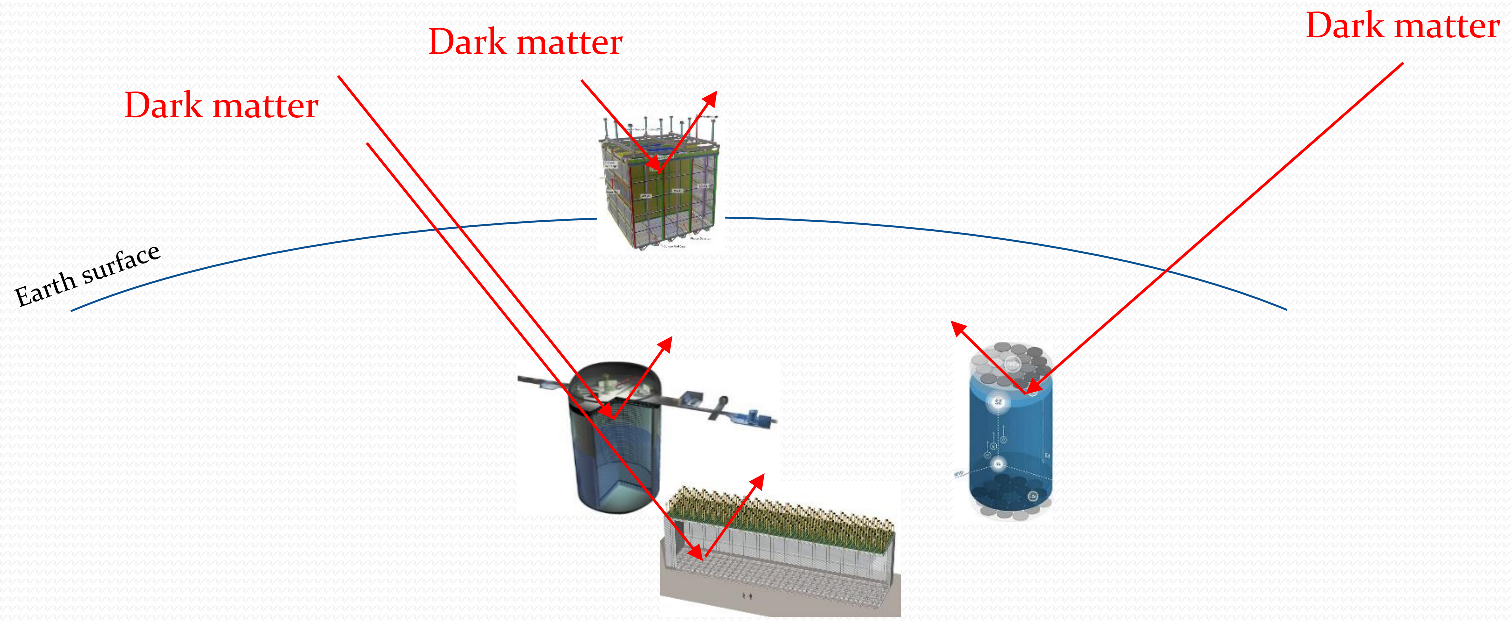



- Quite a few phenomenological studies/proposals in the context of dark photon decays, elastic/inelastic scattering of DM, etc. [LoSecco et al. (1980); Bjorken, Essig, Schuster, Toro (2009); Batell, Pospelov, Ritz (2009); deNiverville, Pospelov, Ritz (2011); Izaguirre, Krnjaic, Schuster, Toro (2014); Izaguirre, Kahn, Krnjaic, Moschella (2017); Berlin, Gori, Schuster, Toro (2018); Bonivento, **DK**, Park, Shin in progress, and many more]

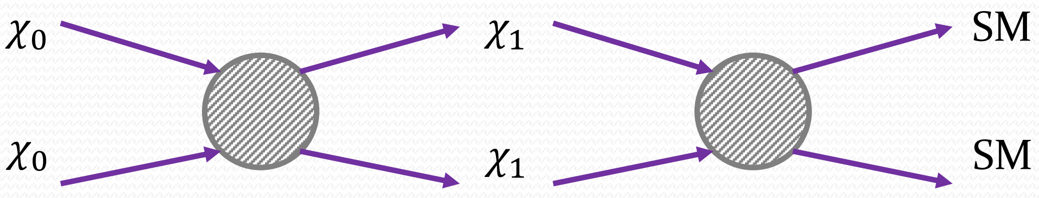
# Boosted/Relativistic Dark Matter: Cosmic Frontier




- Simply waiting for signals coming from the universe today
- (Often) doing nontrivial model building to create boosted dark matter (an example mechanism in the next slide)
- (Typically) probing cosmological dark matter (nonrelativistic) through its boosted “partners”

# Two-component Boosted DM Scenario

- A possible relativistic source: BDM scenario, stability of the two DM species ensured by separate symmetries, e.g., $Z_2 \otimes Z_2'$, $U(1) \otimes U(1)'$, etc.



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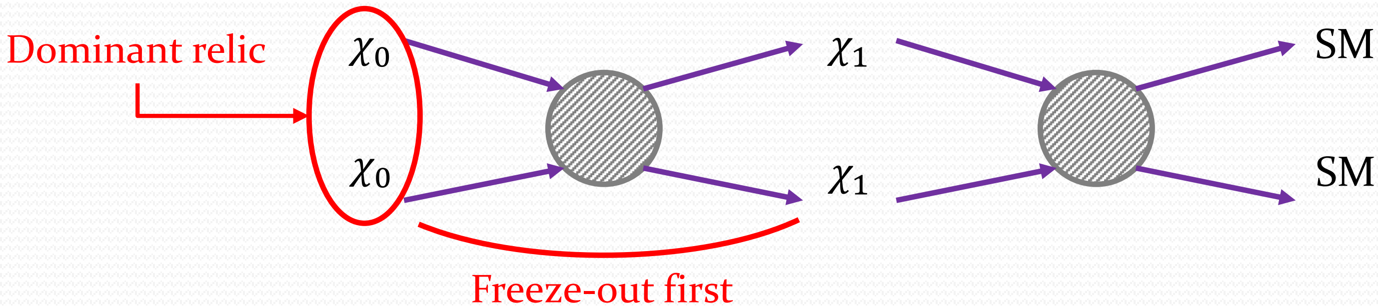


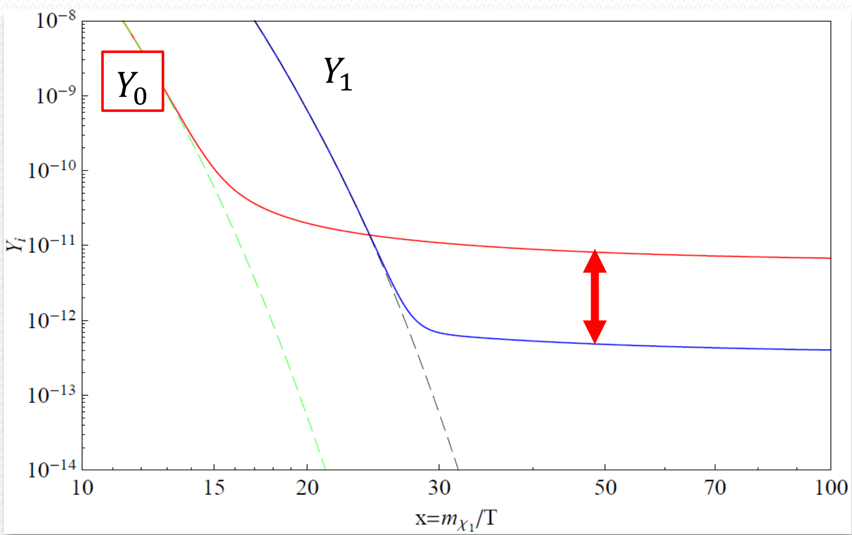


<u>"Assisted" freeze-out</u> mechanism

[Belanger, Park (2011)]

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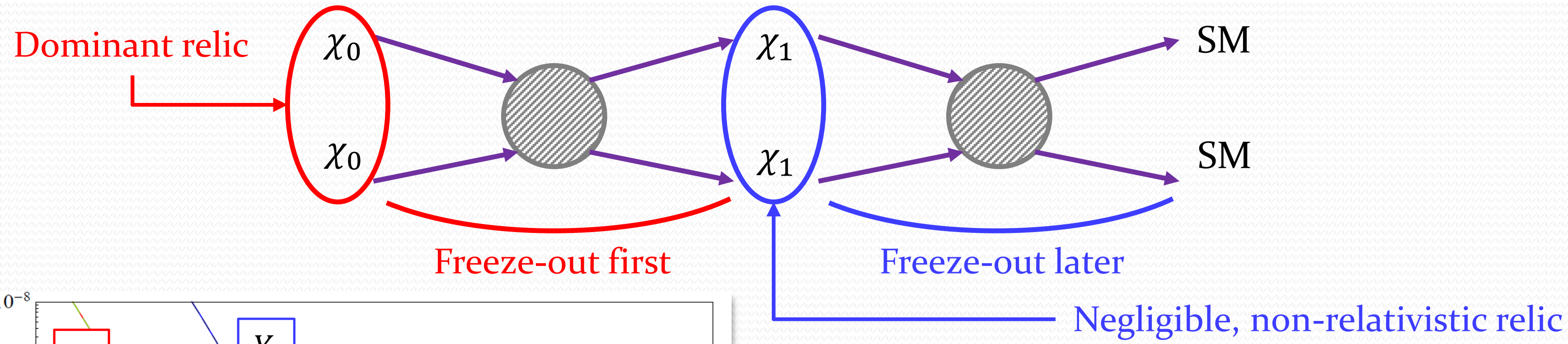


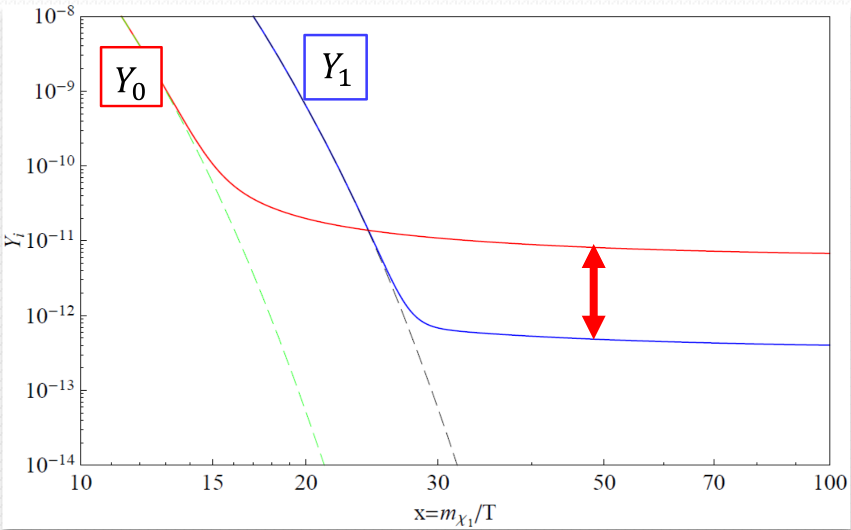


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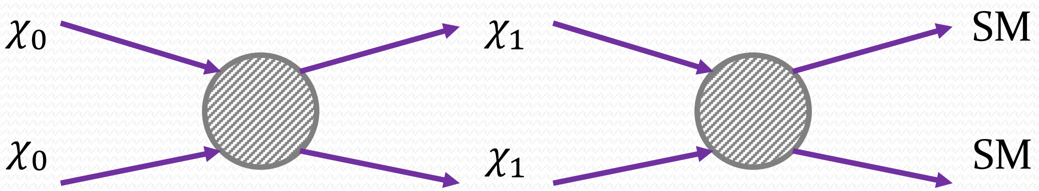
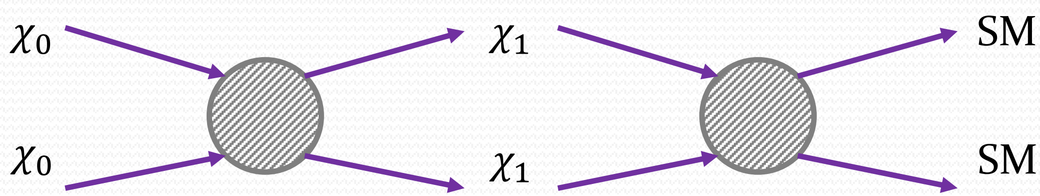
# “Relativistic” Dark Matter Search




- ✓ Heavier relic $\chi_0$: hard to detect it due to tiny/negligible coupling to SM
- ✓ Lighter relic $\chi_1$: hard to detect it due to small amount

# “Relativistic” Dark Matter Search

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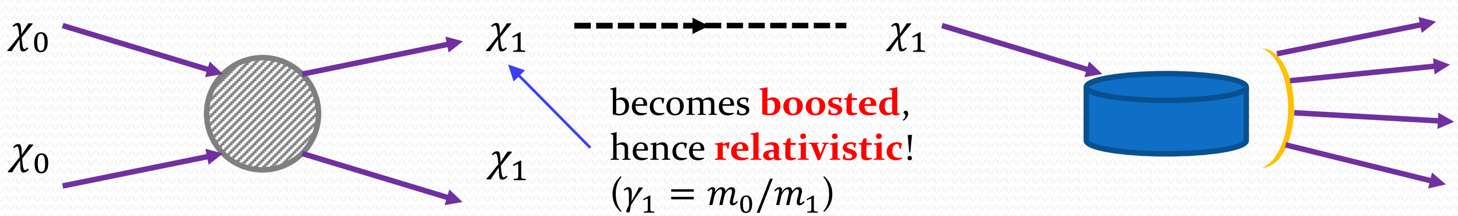



(Galactic Center at the universe **today**) (Laboratory)

[Agashe, Cui, Necib, Thaler (2014)]

# Other Mechanisms

- Boosted dark matter from decaying dark matter [Bhattacharya, Gandhi, Gupta (2014); Kopp, Liu, Wang (2015); **DK**, Park, Park, Shin, in progress]
- Semi-annihilation in e.g., $Z_3$ models [D'Eramo, Thaler (2010)]
- Fast-moving DM via induced nucleon decays [Huang, Zhao (2013)]
- Energetic cosmic-ray-induced (semi-)relativistic dark matter scenarios [Yin (2018); Bringmann, Pospelov (2018); Ema, Sala, Sato (2018)]

# Flux of Boosted Dark Matter

- Flux of boosted $\gamma$ near the earth

$$\mathcal{F}_\gamma \propto (\text{interaction strength}) \times (\chi_0 \text{ number})^2$$

$$\sim 0.8 \times 10^{-7} \text{cm}^{-2} \text{s}^{-1} \left(\frac{\langle \sigma v \rangle_{\chi_0 \chi_0 \to \gamma\gamma}}{10^{-26} \text{cm}^3 \text{s}^{-1}}\right) \left(\frac{20 \text{ GeV}}{m_0}\right)^2$$

# Flux of Boosted Dark Matter

- Flux of boosted $\chi_1$ near the earth

$$\mathcal{F}_{\chi_1} \propto (\text{interaction strength}) \times (\chi_0 \text{ number})^2$$

$$\sim 0.8 \times 10^{-7}\text{cm}^{-2}\text{s}^{-1} \left(\frac{\langle \sigma v \rangle_{\chi_0\chi_0 \to \chi_1\chi_1}}{10^{-26}\text{cm}^3\text{s}^{-1}}\right)\left(\frac{20 \text{ GeV}}{m_0}\right)^2$$

from DM number density

- Setting $\langle \sigma v \rangle_{\chi_0\chi_0 \to \chi_1\chi_1}$ to be $\sim 10^{-26}$ $\text{cm}^3\text{s}^{-1}$ and assuming Navarro-Frenk-White DM halo profile, a standard profile, one finds

$\mathcal{F}_{\chi_1} \sim 10^{-7}\text{cm}^{-2}\text{s}^{-1}$ for WIMP mass-range $\chi_0$ [e.g., $\mathcal{O}(20 \text{ GeV})$]

# Search Proposals at Large-Mass Detectors

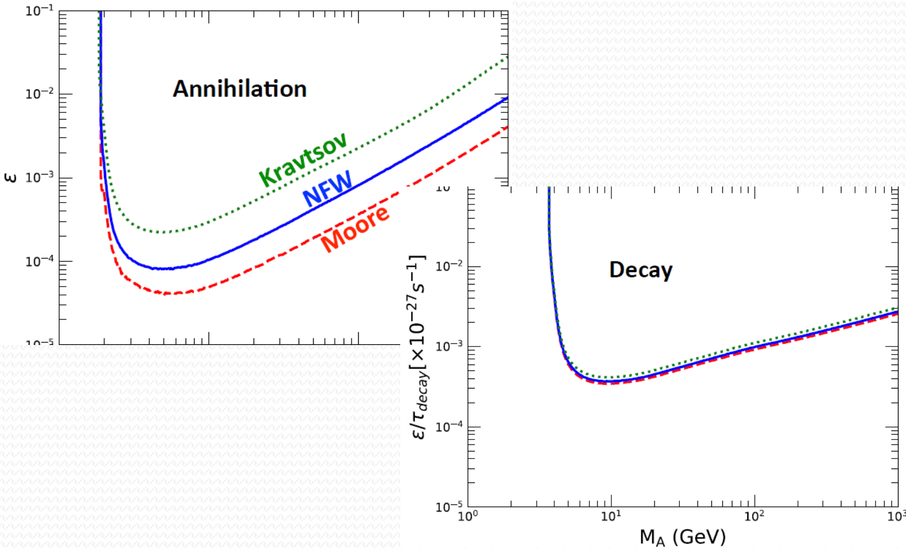
- No sensitivity in conventional (small-mass, say, $< 1$ ton) dark matter direct detection experiments

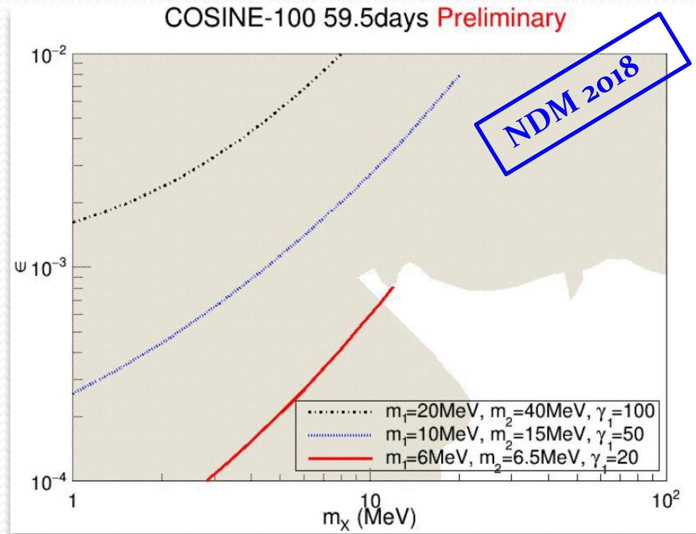
  $\Rightarrow$ large-mass neutrino and/or dark matter detectors motivated

# Search Proposals at Large-Mass Detectors

- ❑ No sensitivity in conventional (small-mass, say, < 1 ton) dark matter direct detection experiments
  ⇒ large-mass neutrino and/or dark matter detectors motivated
- ❑ Example detectors and pheno. studies include
  - ✓ Super-K/Hyper-K [Agashe, Cui, Necib, Thaler (2014); Berger, Cui, Zhao (2014); Kong, Mohlabeng, Park (2014); Necib, Moon, Wongjirad, Conrad (2016); **DK**, Park, Shin (2016)]
  - ✓ DUNE [Necib, Moon, Wongjirad, Conrad (2016); Alhazmi, Kong, Mohlabeng, Park (2016); **DK**, Park, Shin (2016); Alhazmi, Dienes, **DK**, Kong, Park, Shin, Thomas, in progress]
  - ✓ IceCube/PINGU [Agashe, Cui, Necib, Thaler (2014); Bhattacharya, Gandhi, Gupta (2014); Kong, Mohlabeng, Park (2014); Kopp, Liu, Wang (2015); **DK**, Park, Park, Shin, in progress]
  - ✓ Dark Matter detectors (Xenon1T, LZ, etc) [Cherry, Frandsen, Shoemaker (2015); Giudice, **DK**, Park, Shin (2017); Bringmann, Pospelov (2018)]
  - ✓ Surface-based detectors (e.g., ProtoDUNE, SBN etc) [Chatterjee, De Roeck, **DK**, Moghaddam, Park, Shin, Whitehead, Yu (2018), **DK**, Kong, Park, Shin (2018)]

# Experimental Effort




- ❑ Elastic boosted dark matter search in electron scattering channel at the SK detector [SK Collaboration, PRL (2018)]
- ❑ Inelastic boosted dark matter search at the COSINE detector (an official result will appear soon).

- ❑ Inelastic boosted dark matter search planned in DUNE, ProtoDUNE, and ICARUS (Gran Sasso data)
- ❑ Elastic boosted dark matter search planned in DUNE (see Josh's and Yun-Tse's talks)

# Many More Well-Motivated Experiments

| DM Experiment | Target Material | Volume [t] Active | Fiducial | Depth [m] | $E_{\rm th}$ [keV] | Position [cm] | Resolution Angular [°] | Energy [%] | PID | Run Time | Refs. |
|---|---|---|---|---|---|---|---|---|---|---|---|
| DarkSide -50 | LAr DP-TPC | 46.4 kg | 36.9 kg | 3,800 m.w.e. | $\mathcal{O}(1)$ | $\sim 0.1-1$ | – | ? | – | 2013- | [83] |
| DarkSide -20k | LAr DP-TPC | 23 | 20 | 3,800 m.w.e. | $\mathcal{O}(1)$ | $\sim 0.1-1$ | – | ? | – | goal: 2021- | [30] |
| XENON1T | LXe DP-TPC | 2.0 | 1.3 | 3,600 m.w.e. | $\mathcal{O}(1)$ | $\sim 0.1-1$ | – | ? | – | 2016 -2018 | [85, 100] |
| XENONnT | LXe DP-TPC | 5.9 | $\sim 4$ | 3,600 m.w.e. | $\mathcal{O}(1)$ | $\sim 0.1-1$ | – | ? | – | goal: 2019- | [100] |
| DEAP -3600 | SP LAr S1 only | 3.26 | 2.2 | 2,000 | $\mathcal{O}(10)$ | $< 10$ | – | ? | – | 2016- | [86, 87] |
| DEAP -50T | SP LAr S1 only | 150 | 50 | 2,000 | $\mathcal{O}(10)$ | $\mathcal{O}(10)$ | – | ? | – | – | [86] |
| LUX-ZEPLIN | LXe DP-TPC | 7 | 5.6 | 4,300 m.w.e. | $\mathcal{O}(1)$ | $\sim 0.1-1$ | – | ? | – | goal: 2020- | [88] |
| **Neutrino Experiment** | **Target Material** | **Volume [kt] Active** | **Fiducial** | **Depth [m]** | **$E_{\rm th}$ [MeV]** | **Vertex [cm]** | **Resolution Angular [°]** | **Energy [%]** | **PID** | **Run Time** | **Refs.** |
| Borexino | organic LS | 0.278 | 0.1 | 3,800 m.w.e. | $\sim 0.2$ | ~9-17 | ? | $\frac{5}{\sqrt{E\,(\rm MeV)}}$ | ? | $> 5.6$ year | [89] |
| KamLAND | LS | 1 | 0.2686 | 1,000 | 0.2 - 1 | $\frac{12-13}{\sqrt{E\,(\rm MeV)}}$ | ? | $\frac{6.4-6.9}{\sqrt{E\,(\rm MeV)}}$ | ? | $\sim 10$ year? | [90, 91] |
| JUNO | LS | – | 20 | 700 | $< 1$, goal: 0.1 | $\frac{12}{\sqrt{E\,(\rm MeV)}}$ | $\mu$: $L > 5$ m: $< 1$, $L > 1$ m: $< 10$ | $\frac{3}{\sqrt{E\,(\rm MeV)}}$ | $\mu^+$ vs $\pi^+$, $e^+$ vs $\pi^0$: difficult | goal: 2020- | [92] |
| DUNE | LArTPC | Total: 17.5 ×4 | (SP: 10 + DP: 10.6) ×2 | 1500 | $e: 30$, $p$: 21-50 | 1-2 | $e, \mu, \pi^\pm: 1$, $p, n: 5$ | $e: 1 \oplus \frac{15}{\sqrt{E\,(\rm MeV)}}$ $p: 10\,(p < 0.4\,{\rm GeV})$, $5 \oplus \frac{30}{\sqrt{E\,(\rm GeV)}}$ $(p > 0.4\,{\rm GeV})$ | good $e, \mu, \pi^\pm, p$ separation | 10 kt: 2025-, 20 kt: 2026- | [6, 31–33] |
| SK | Water Cherenkov | Total: 50 | 22.5 | 1,000 | $e: 5$, $p: 1.07$ GeV | 5 MeV: 95, 10 MeV: 55, 20 MeV: 40 | 10 MeV: 25, 0.1 GeV: 3, 1.33 GeV: 1.2 | 10 MeV: 16, 1 GeV: 2.5 | $e, \mu$: good | $\gtrsim 15$ year | [93–95] |
| HK | Water Cherenkov | Total: 258 ×2 | 187 ×2 | Japan: 650, Korea: 1,000 | $e: < 5$, $p: 1.07$ GeV | 5 MeV: 75, 10 MeV: 45, 15 MeV: 40, 0.5 GeV: 28 | similar to SK | better than SK | $e, \mu$: good, $\pi^0, \pi^\pm$: mild | goal: 2026- | [34–36] |
| | **Target Material** | **Effective Volume [Mt]** | | **Depth [m]** | **$E_{\rm th}$ [GeV]** | **Vertex [m]** | **Resolution Angular [°]** | **Energy [%]** | **PID** | **Run Time** | **Refs.** |
| IceCube | Ice Cherenkov | 100 GeV: $\sim 30$, 200 GeV: $\sim 200$ | | 1,450 Ice | $\sim 100$ | vertical: 5, horizontal: 15 | $\mu$-track: $\sim 1$, shower: $\sim 30$ | $\sim 15$ | only $\mu$ | 2011- (2008) | [96] |
| DeepCore | Ice Cherenkov | 10 GeV: $\sim 5$, 100 GeV: $\sim 30$ | | 2,100 Ice | $\sim 10$ | better | $\mu$-track: ~1, shower: $\gtrsim 10$ | ? | only $\mu$ | 2011- (2010) | [37] |
| PINGU | Ice Cherenkov | 1 GeV: $\sim 1$, 10 GeV: $\sim 5$ | | 2,100 Ice | $\sim 1$ | much better | 1 GeV: 25, 10 GeV: 10 | ? | only $\mu$ | > 2023 | [97] |
| Gen2 | Ice Cherenkov | $\sim 10$ Gt | | 1,360 Ice | $\sim 50$ TeV | worse | $\mu$-track: $< 1$ shower: $\sim 15$ | ? | only $\mu$ | – | [98] |

- ❑ Many existing/upcoming experiments which are potentially capable of testing models conceiving boosted dark matter
- ❑ Additional physics opportunity on top of the main missions of experiments

[**DK**, Machado, Park, Shin, in progress]

# Questions

For a model,

- Parameter space to which an experiment would be best sensitive?
- Better-motivated channels to investigate in terms of signal searches?

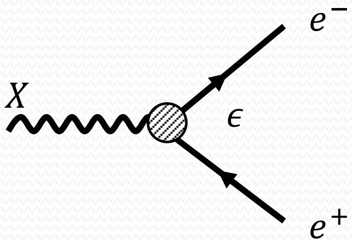
# Topics in the Rest of the Talk

- Proton scattering vs. DIS in elastic/inelastic BDM searches
- Proton scattering vs. electron scattering in elastic/inelastic BDM searches
- Example data analysis (in DUNE and Hyper-K)

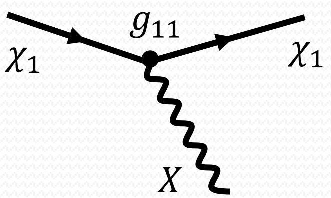
# Benchmark Model: Building Blocks

$$\mathcal{L}_{\rm int} \ni -\frac{\epsilon}{2}F_{\mu\nu}X^{\mu\nu} + g_{11}\bar{\chi}_1\gamma^\mu\chi_1 X_\mu + g_{12}\bar{\chi}_2\gamma^\mu\chi_1 X_\mu + \mathrm{h.c.} + (\mathrm{others})$$

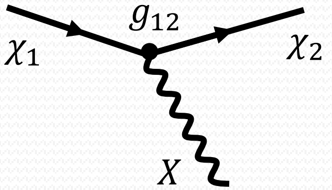
- Vector portal (e.g., dark photon scenario)



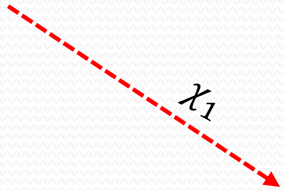

- Fermionic DM
  - $\chi_2$: a heavier (unstable) dark-sector state
  - Flavor-conserving interaction $\Rightarrow$ elastic scattering




  - Flavor-changing interaction $\Rightarrow$ inelastic scattering



# Expected BDM Signatures: Elastic Scattering



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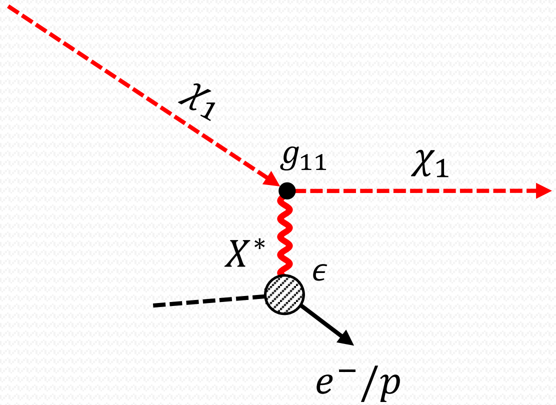

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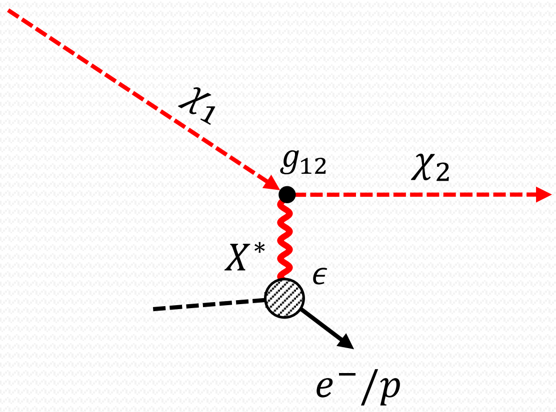

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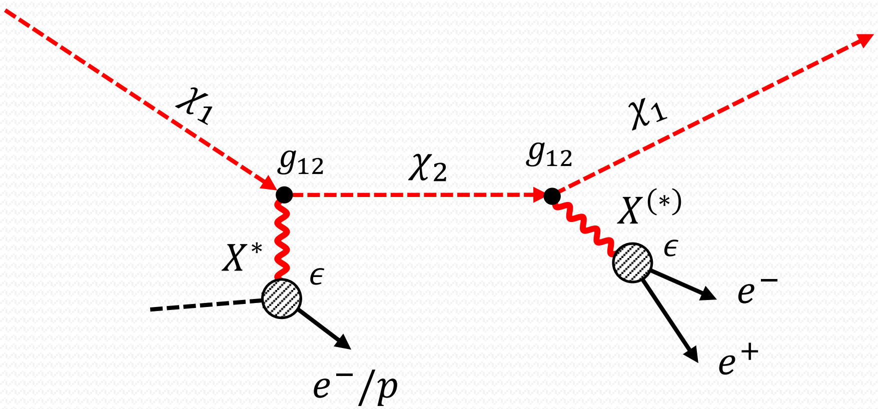

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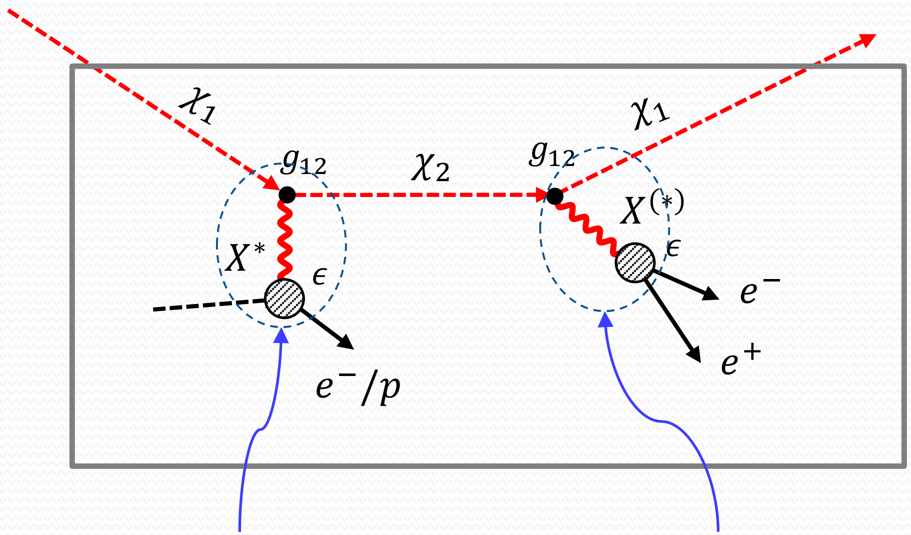


$p$- or $e$-scattering (primary)

Decay (secondary)

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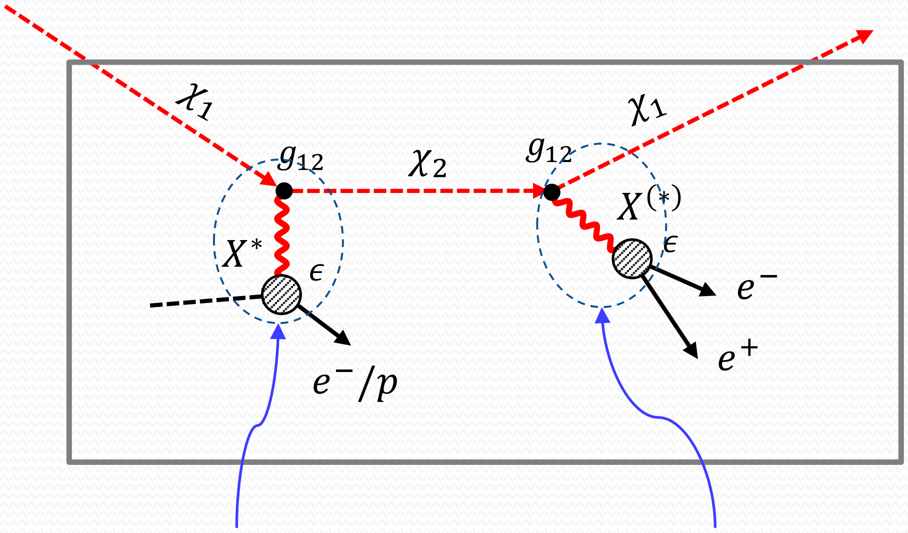
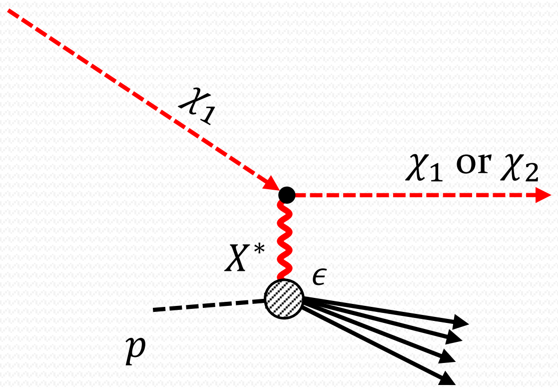


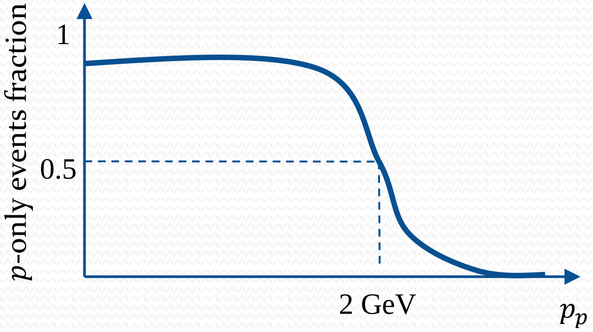

$p$- or $e$-scattering (primary)    Decay (secondary)

- Everything happens inside a detector fiducial volume.
- The secondary interaction point may be displaced due to either long-lived
  - ✓ $\chi_2$ – when it decays via an off-shell $X$ (i.e., $m_2 < m_1 + m_X$) – or
  - ✓ on-shell $X$ – when kinetic mixing parameter is sufficiently small.
- If $\delta m = m_2 - m_1$ is large enough, other final states (e.g., $\mu^+\mu^-$, $\pi^+\pi^-$, etc) are available.

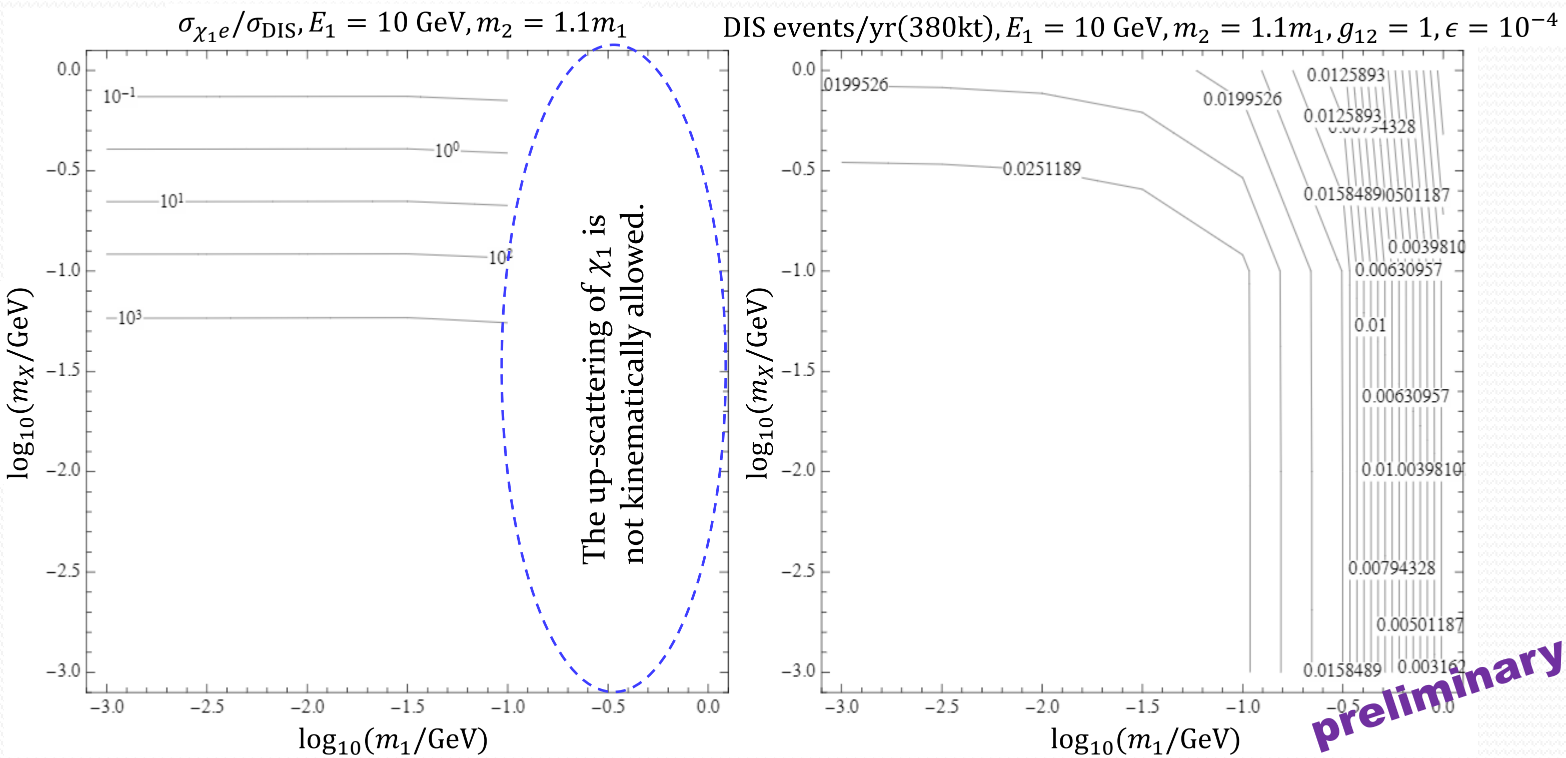
# $p$-Scattering vs. DIS




- If a momentum transfer is too large, a proton may break apart.
- What is large? ⇒ A Super-K simulation study [Fechner et al, PRD (2009)] showed about 50 % events accompany (at least) a pion or a secondary particle for $p_p \approx 2$ GeV.
- We categorize any event with $p_p < 2$ GeV as the $p$-scattering (i.e., simplified step-function-like transition).

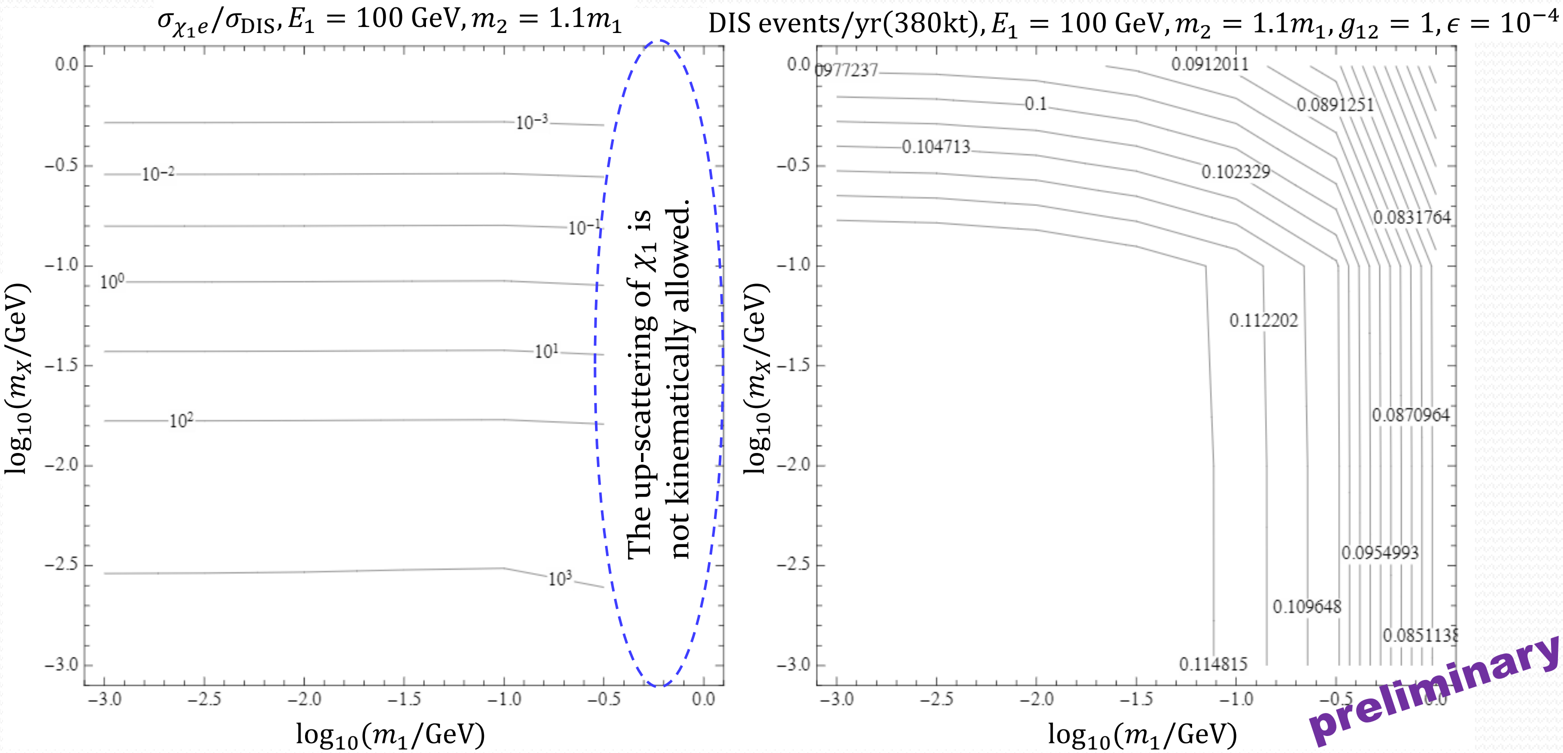


# $p$-Scattering vs. DIS: Numerical Study




- ❑ We study $\sigma_{\chi_1 e}/\sigma_{\text{DIS}}$ first ($\sigma_{\chi_1 p}/\sigma_{\text{DIS}}$ coming up), but due to $\sigma_{\chi_1 p} > \sigma_{\chi_1 e}$ over the parameter space of interest (in a few slides), the argument later on holds.
- ❑ For sub-GeV or lighter mediator (here dark photon), $p$-scattering dominates over DIS.
- ❑ Even in the region where DIS is sizable, the expected number of DIS events is small.

# $p$-Scattering vs. DIS: Numerical Study




- DIS-preferred region expands, but a similar observation still holds with higher incoming energy of $\chi_1$.
- ($\chi_1$ with $E_1 > 100$ GeV may come with too small flux, depending on the underlying "boost" mechanism.)

# (Semi-)analytic Understanding

- $p$-scattering:

$$\underbrace{\frac{d\sigma_{\chi_1 p}}{dp_p} \propto \frac{1}{\{2m_p(E_2 - E_1) - m_X^2\}^2}}_{t\text{-channel propagator}} \simeq \frac{1}{({p_p}^2 + m_X^2)^2}$$

$t$-channel propagator

in the limit of $p_p \ll m_p$

- ✓ The differential cross section is peaking towards small recoil momentum.
- ✓ $p$-scattering cross section rises in decreasing $m_X(\ll m_p \approx 1$ GeV) as long as $p_p \lesssim m_X$.

# (Semi-)analytic Understanding

- $p$-scattering:

$$\frac{d\sigma_{\chi_1 p}}{dp_p} \propto \underbrace{\frac{1}{\{2m_p(E_2 - E_1) - m_X^2\}^2}}_{t\text{-channel propagator}} \simeq \frac{1}{({p_p}^2 + m_X^2)^2}$$

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- DIS:

$$\frac{d^2\sigma_{\rm DIS}}{dxdy} \propto \frac{1}{(Q^2 + m_X^2)^2} \approx \frac{1}{Q^4}$$

- ✓ The energy transfer $Q$ is larger than ~2 GeV, and in turn, much larger than $m_X (\ll 1$ GeV) under consideration.
- ✓ DIS cross section does not vary much in decreasing $m_X (\ll m_p \approx 1$ GeV).

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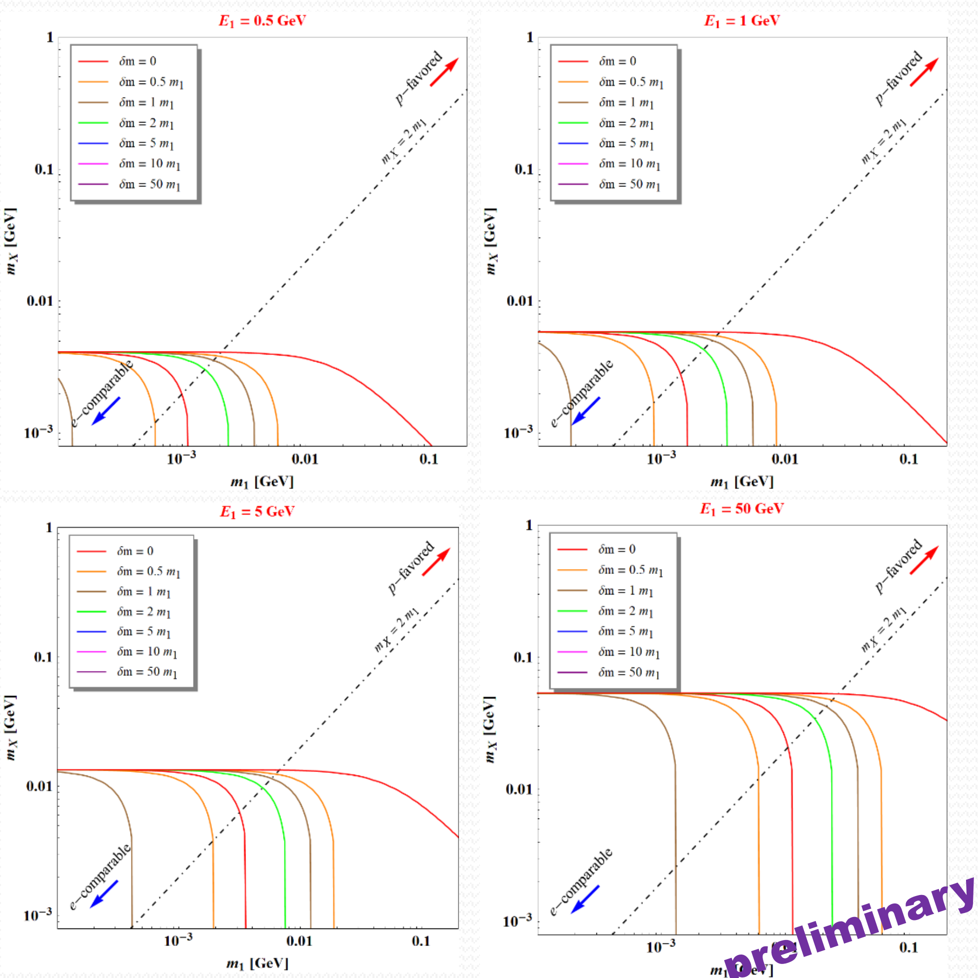
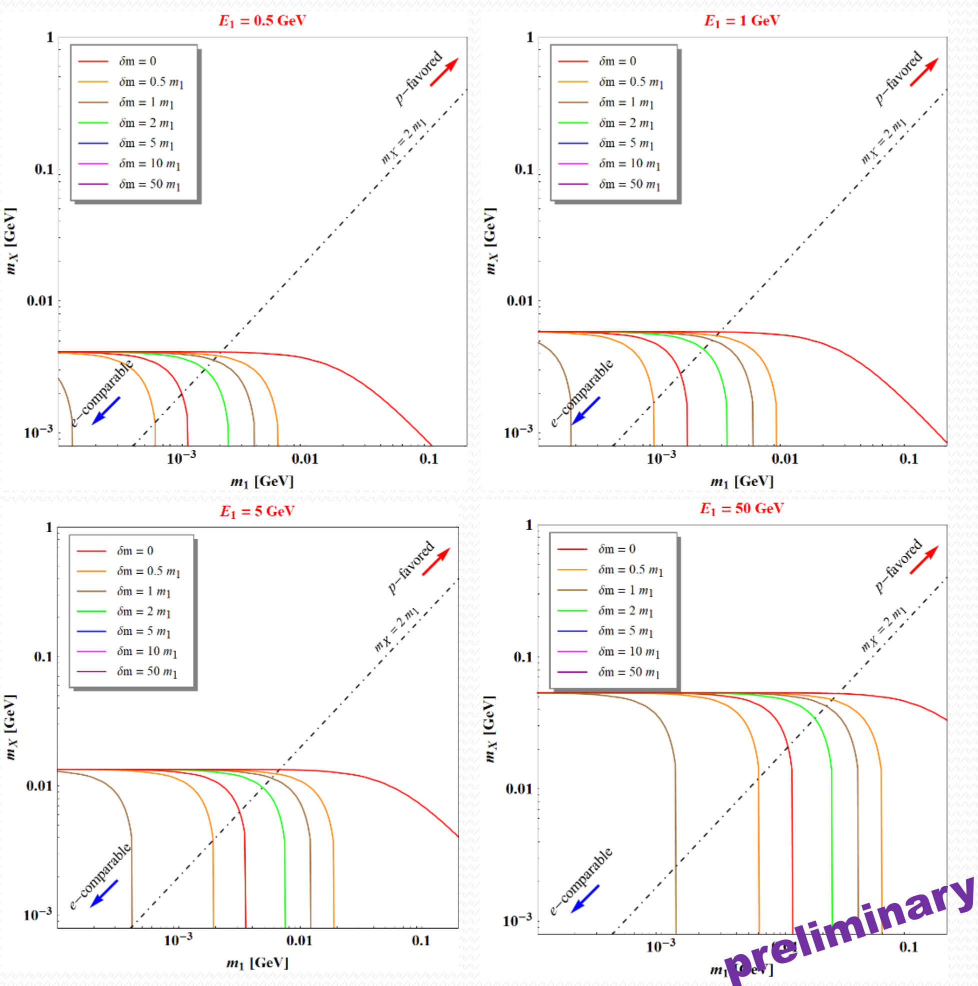
- Our numerical study suggests that $\sigma_{\chi_1 p}$ be larger than $\sigma_{\rm DIS}$ for $m_X \approx 0.1$ GeV and $E_1 < 100$ GeV.
- As far as a mediator is within sub-GeV or smaller, DIS-induced events, which often involve complicated final states, would be negligible (cf. neutrino-induced DIS via $\mathcal{O}(100$ GeV) $W/Z$ gauge boson exchange).

# $p$-Scattering vs. $e$-Scattering: Theory Level




- A "perfect" detector (no resolution issue, no energy threshold, secondary decay appearing inside the detector) is assumed, only with $p_p < 2$ GeV taken into consideration.
- Boundaries are defined by $\sigma_{\chi_1 e} = 0.9\sigma_{\chi_1 p}$ as the $p$-scattering cross section is at least slightly greater than the $e$-scattering over the region of interest.

# $p$-Scattering vs. $e$-Scattering: Moral




- If a BDM search hypothesizes a heavy dark photon (say, sub-GeV range), the proton channel may expedite discovery.
- If a model conceiving inelastic BDM (iBDM) signals allows for large mass gaps between $\chi_1$ and $\chi_2$, the proton channel is more advantageous.
- On the other hand, the electron channel becomes comparable/complementary in probing the parameter regions with smaller $m_1$ and $m_X$.
- As the boosted $\chi_1$ comes with more energy, more parameter space where the electron channel is comparable opens up.

# $p$-Scattering vs. $e$-Scattering: a DUNE-like Detector

- Selection criteria

i) $p_e > 30$ MeV, $30\,\text{MeV} < p_p < 2\,\text{GeV}$,

ii) $\Delta\theta_{e-i} > 1°$, $\Delta\theta_{p-i} > 5°$ with $i$ denoting the other visible final state particles, and

iii) both primary and secondary vertices should appear in the detector fiducial volume.

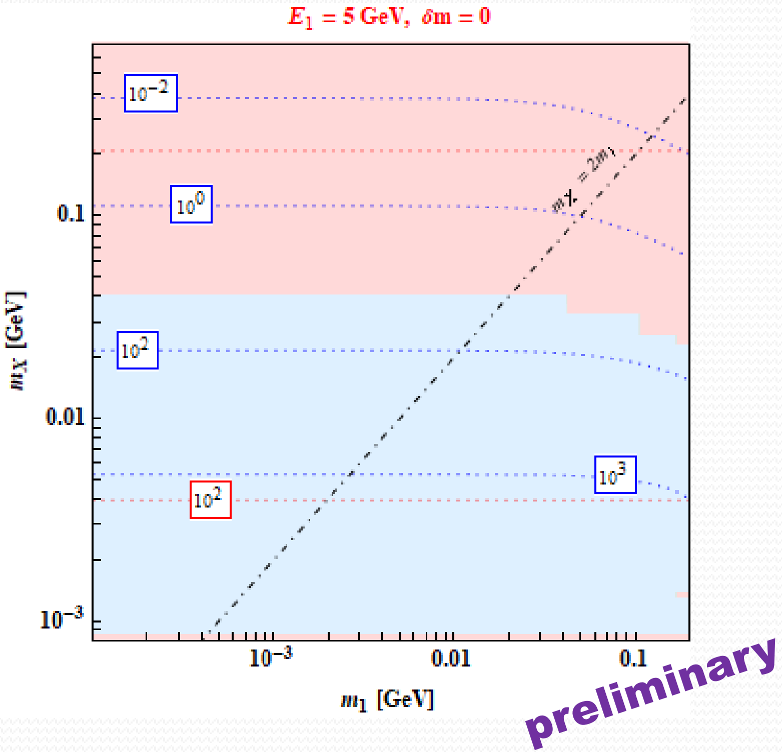
- For each of 5,600 scanning points over the parameter space of interest, we generate 5 million events using the TGenPhaseSpace module in the ROOT package and reweight them with matrix element values.

- The number of expected signal events are calculated by

$$N_{\text{sig}} = \sigma_{\chi_1 p(e)}\,\mathcal{F}_1\,A\,t_{\text{exp}}\,N_{p(e)}$$

with $A$ calculated from considering all selection criteria and 40 kt·yr assumed.

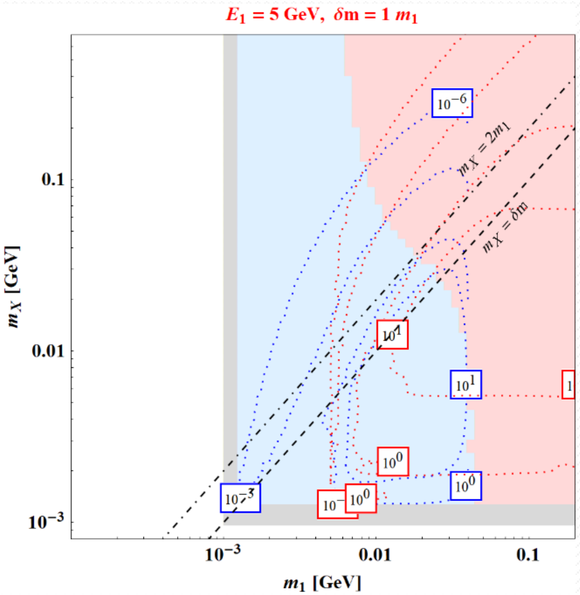
# $p$-Scattering vs. $e$-Scattering: a DUNE-like Detector

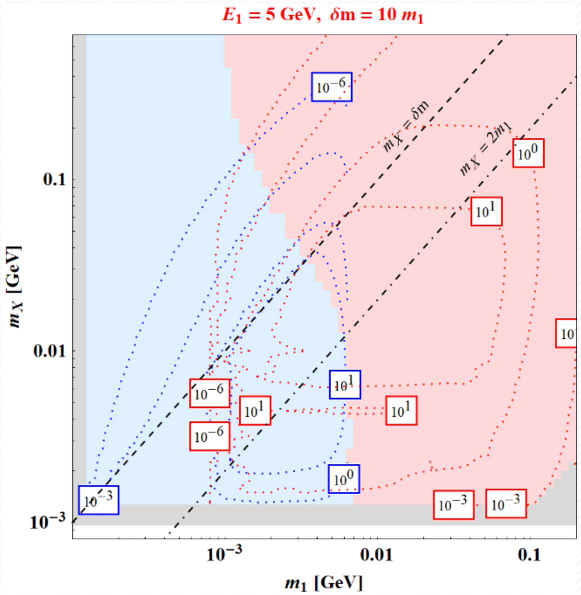



- ❑ $e$-scattering can be larger than $p$-scattering, because more events populate in smaller proton recoil energy, and a harder angular cut on proton rejects some fraction of events.

- ❑ Many signal events would be expected in the region with small $m_X$, but may suffer from large backgrounds such as neutrino-induced events (only target recoil).
  - $\Rightarrow$ Directionality helps to suppress backgrounds.

# $p$-Scattering vs. $e$-Scattering: a DUNE-like Detector




- White regions: kinematically not allowed to create an $e^-e^+$ pair.
- Gray regions: barely allowed to have inelastic BDM events, but fail to pass cuts.
- $e$-scattering can be larger than $p$-scattering, because more events populate in smaller proton recoil energy, and a harder angular cut on proton rejects some fraction of events.
- $e$-scattering preferred region with large $m_X$, the $e^-e^+$ pair in the $p$-channel often fails to pass angle cut.

# $p$-Scattering vs. $e$-Scattering: a HK-like Detector

- Selection criteria

  i) $p_e > 100$ MeV, $1.07\ \text{GeV} < p_p < 2$ GeV,

  ii) $\Delta\theta_{e-i} > 3^\circ$, $\Delta\theta_{p-i} > 3^\circ$ with $i$ running over the other visible final state particles, and

  iii) both primary and secondary vertices should appear in the detector fiducial volume.

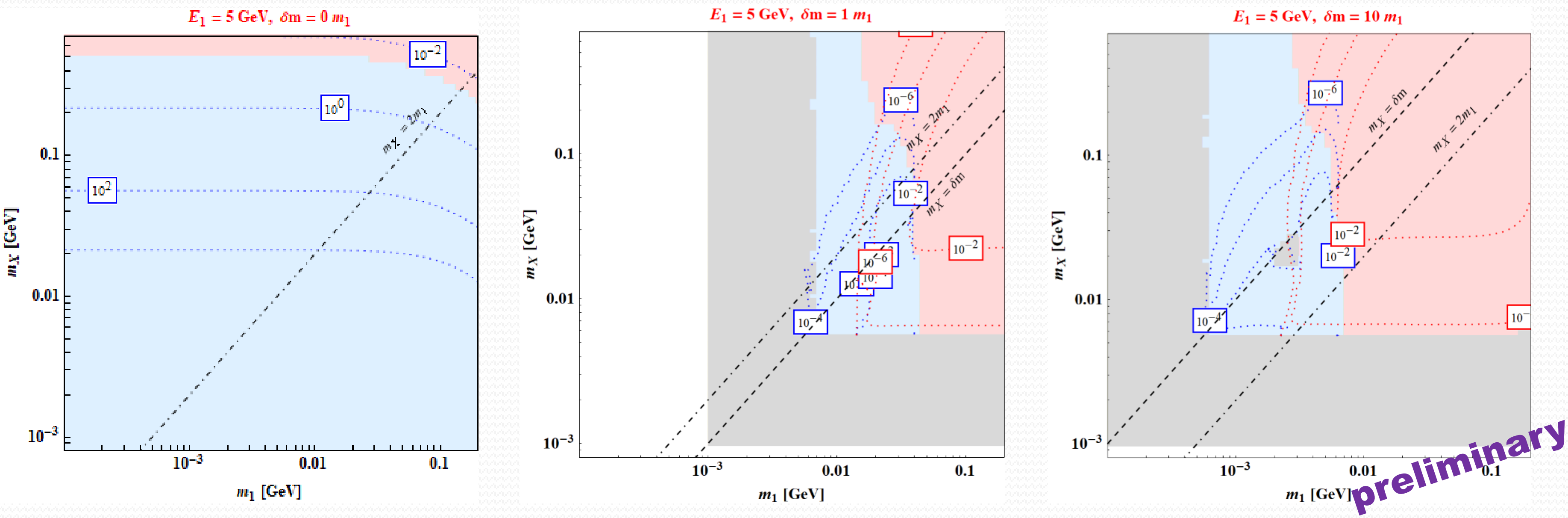
- For each of 5,600 scanning points over the parameter space of interest, we generate 5 million events using the TGenPhaseSpace module in the ROOT package and reweight them with matrix element values.

- The number of expected signal events are calculated by

$$N_{\text{sig}} = \sigma_{\chi_1 p(e)}\, \mathcal{F}_1\, A\, t_{\text{exp}}\, N_{p(e)}$$

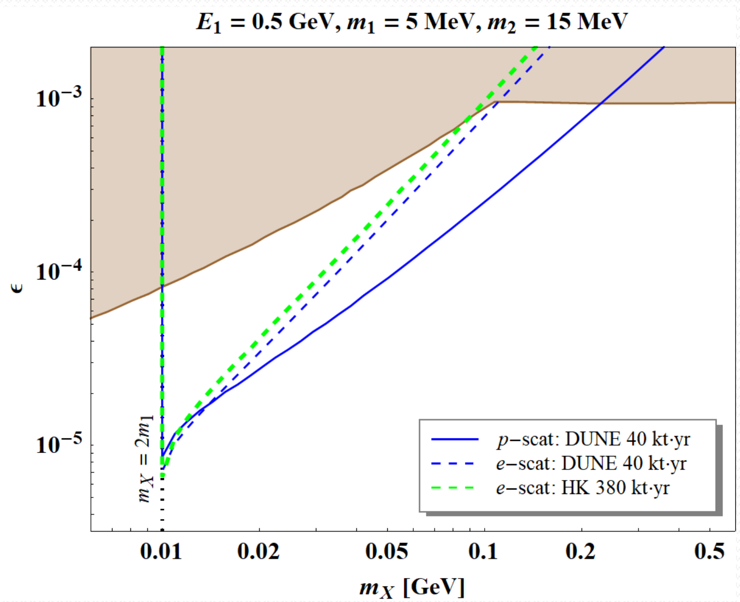
with $A$ calculated from considering all selection criteria and 380 kt·yr assumed.

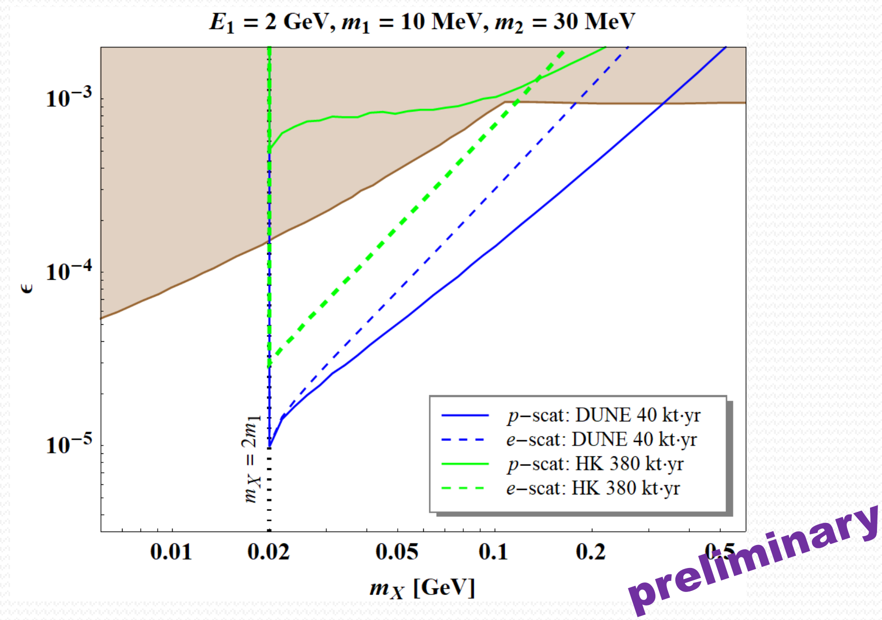
# $p$-Scattering vs. $e$-Scattering: a HK-like Detector




- ❑ $e$-scattering preferred region is significantly extended because a proton needs enough kinetic energy to create Cherenkov radiation.
- ❑ Gray regions become much wider than corresponding results for DUNE due to the larger thresholds and angular resolution. ⇒ In order for HK to probe parameter space with small $m_X$ and/or $m_1$, search strategies getting around these issues are motivated.

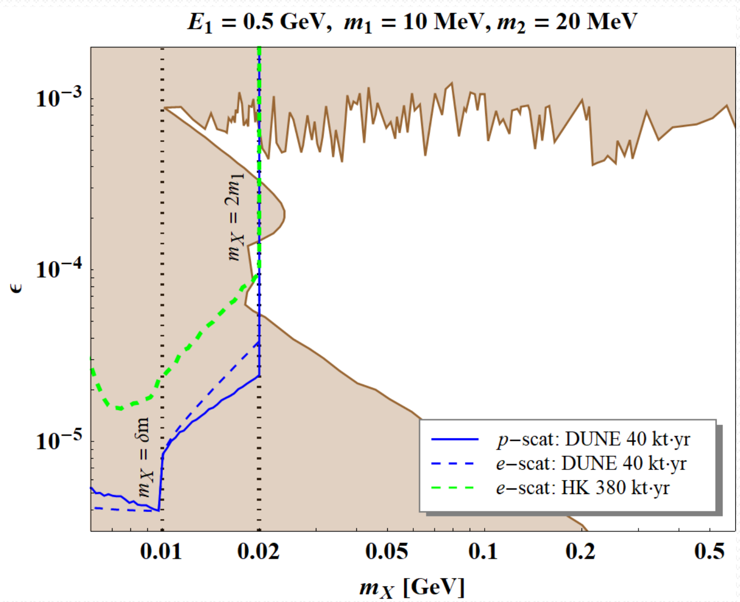
# Exploring Dark Photon Parameter Space: HK vs. DUNE

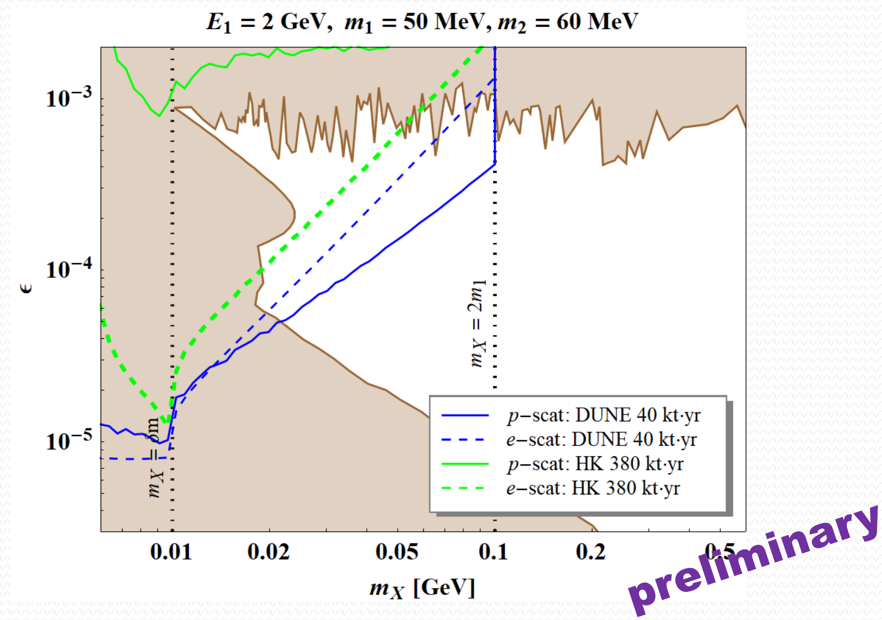



- The exclusion limits are for the case of $m_X > 2m_1$, but $\delta m = m_2 - m_1 < m_X$ so that $\chi_2$ is guaranteed to decay visibly.
- $p$-scattering is advantageous than $e$-scattering in increasing $m_X$ as expected.
- For larger $E_1$, the proton scattering channel in HK begins to cover some region of parameter space.
  - $\Rightarrow$ Better angular resolution, lower threshold energy would enable HK to cover more parameter space.

# Exploring Dark Photon Parameter Space: HK vs. DUNE

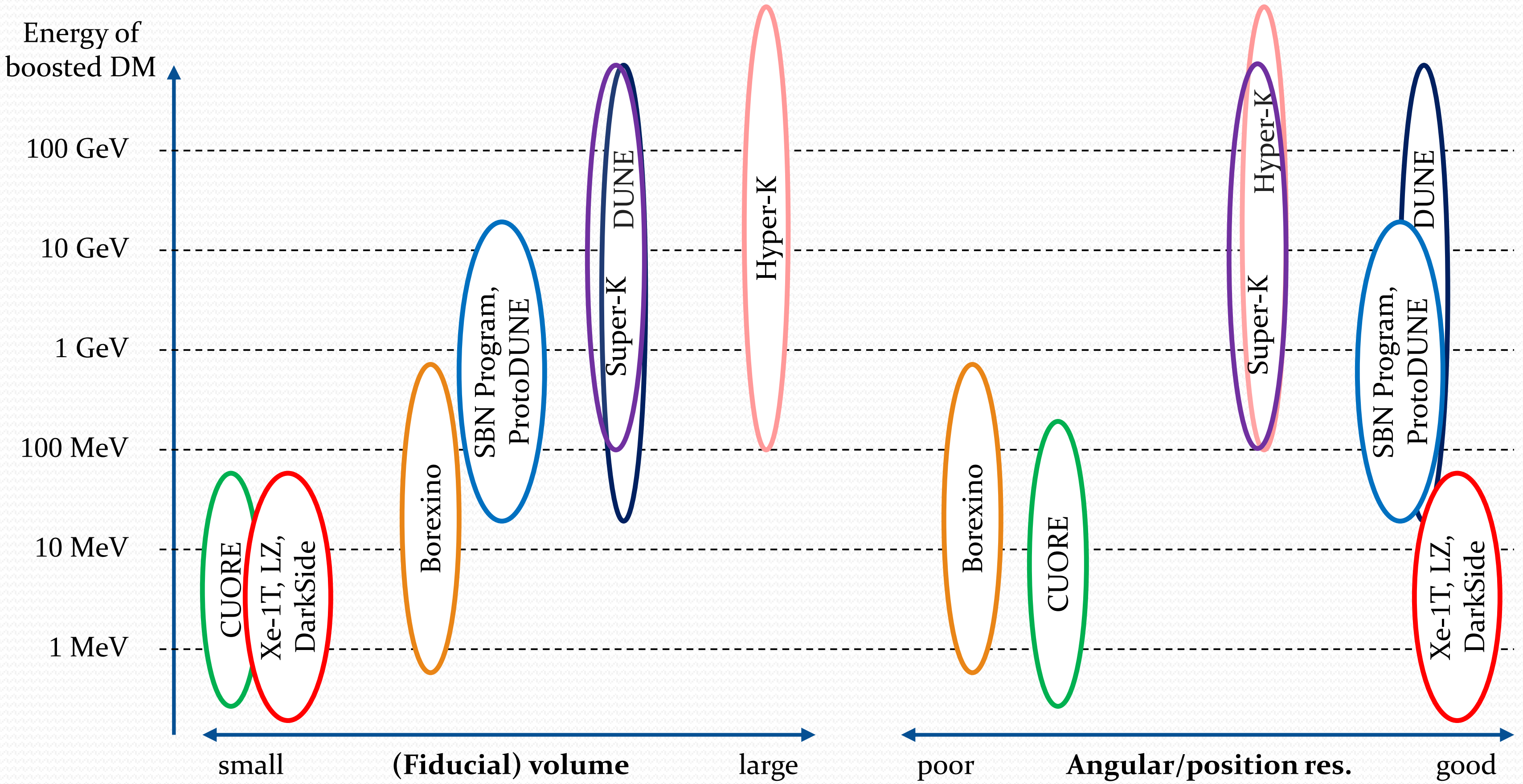


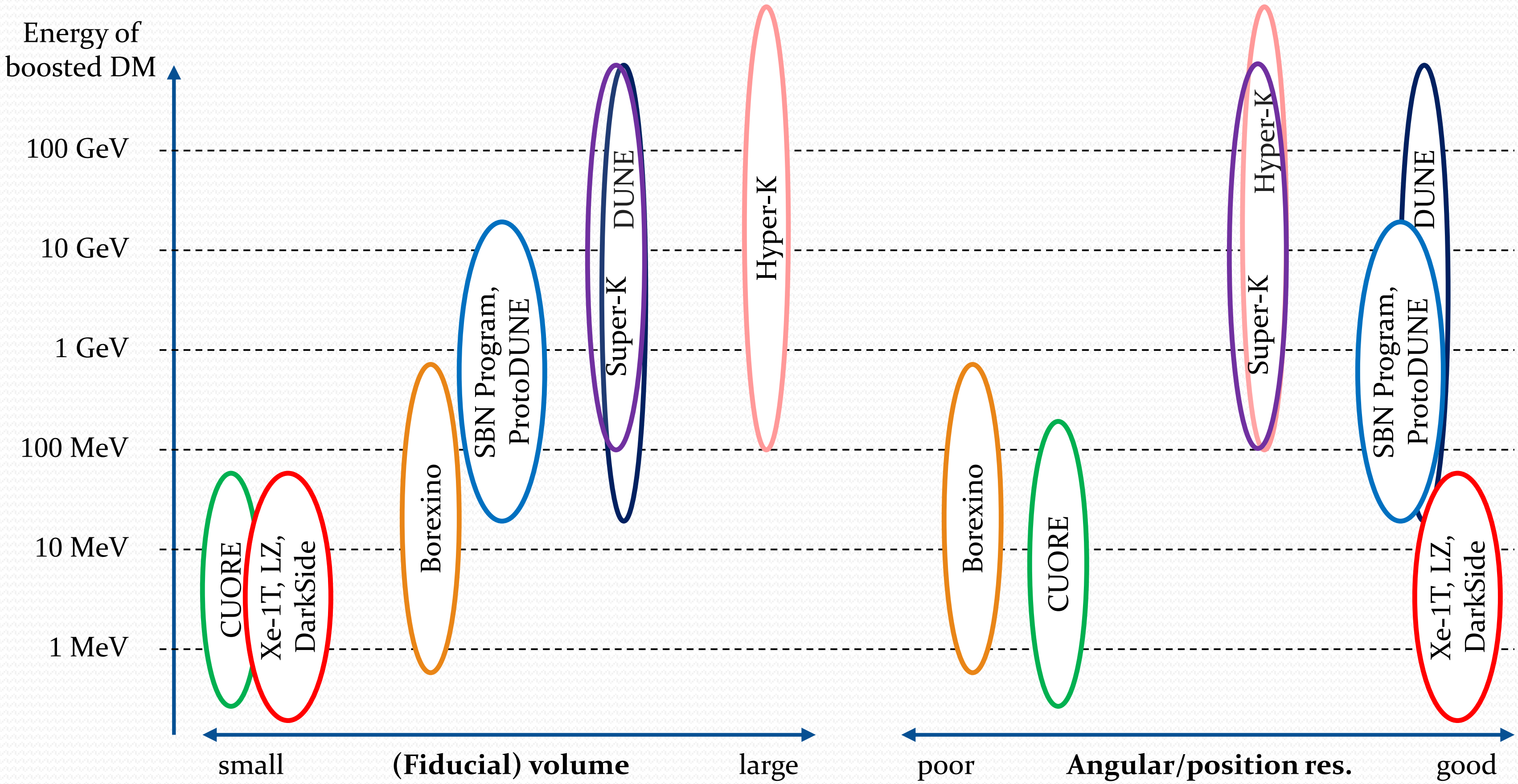

- ❑ The exclusion limits are for the case of $m_X < 2m_1$.
- ❑ $p$-scattering is advantageous than $e$-scattering in increasing $m_X$ as expected.
- ❑ A transition happens at $\delta m = m_X$ where $\chi_2$ decays to an $e^- e^+$ pair through on-shell $X \leftrightarrow$ off-shell $X$.
- ❑ For larger $E_1$, the proton scattering channel in HK begins to cover some region of parameter space.

  $\Rightarrow$ Better angular resolution, lower threshold energy would enable HK to cover more parameter space.

# (In)elastic BDM Searches in Various Experiments



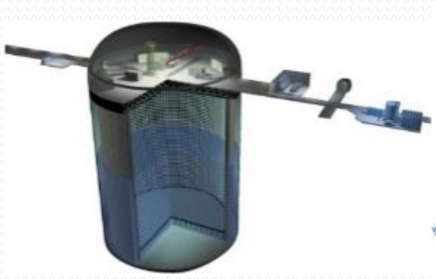
# (In)elastic BDM Searches in Various Experiments

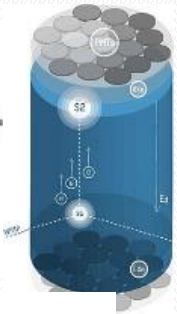


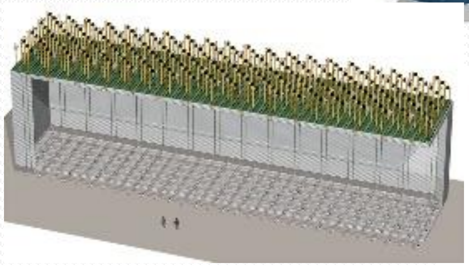

Detectors are **complementary** to one another rather than superior to the others!

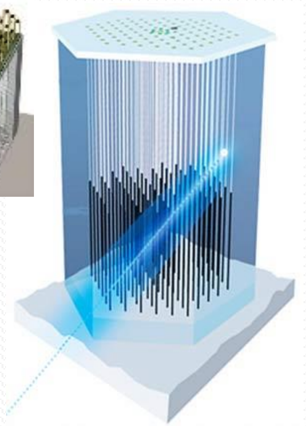
# Conclusions

- Boosted dark matter searches at the cosmic frontier are **promising**.
- They may provide an **alternative avenue** to explore dark sector physics (including dark matter).
- Theoretical/phenomenological studies have been **actively** conducted and in progress.
- There are **many** ongoing/projected **large-volume neutrino/dark matter experiments** in which they can be tested.
- Search strategies and analysis designs **depend on models to explore**.
  - ✓ Elastic vs. inelastic BDM
  - ✓ Proton vs. electron scattering channels
  - ✓ High-performance detectors are better for signals with many features.





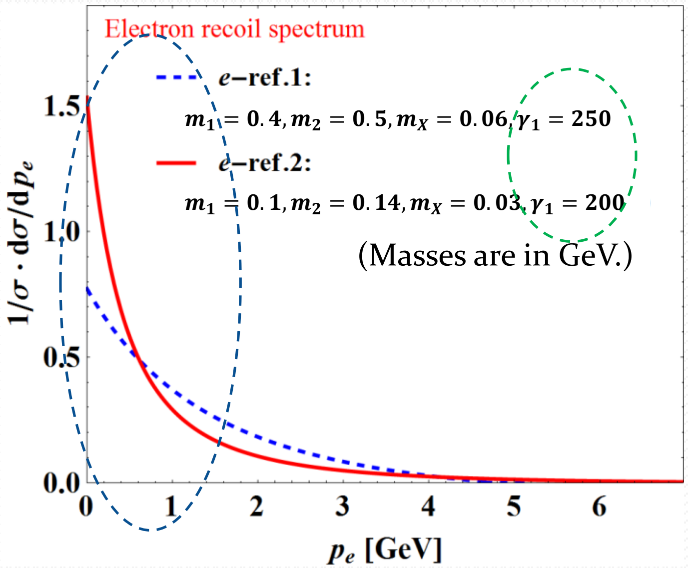




# Back-up

# Generic Features: *e*-scattering - Cross Section

$$\frac{d\sigma}{dE_T} = \underbrace{\frac{m_T}{8\pi\lambda(s, m_T^2, m_1^2)}}_{\text{From PS, same for elastic scattering}} \underbrace{\frac{8(\epsilon e g_{12})^2 m_T}{\{2m_T(E_2 - E_1) - m_X^2\}^2}\left[m_T(E_1^2 + E_2^2) - \frac{(m_2 - m_1)^2}{2}(E_2 - E_1 + m_T) + m_T^2(E_2 - E_1) + m_1^2 E_2 - m_2^2 E_1\right]}_{\text{From matrix element, expression for elastic scattering in the limit of } m_2 \to m_1}$$




- A **large boost factor** is preferred to access heavier dark sector states.
- Cross section is **peaking towards lower energy** electron recoil. (The generic trend is relevant to elastic scattering.)

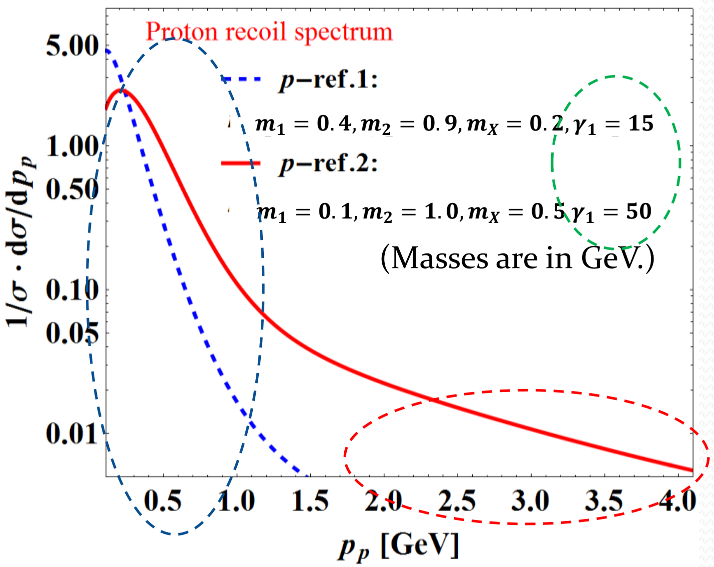
# Generic Features: *p*-scattering - Cross Section

$$\frac{d\sigma}{dE_T} = \frac{m_T}{8\pi\lambda(s, m_T^2, m_1^2)}\overline{|\mathcal{M}|}^2$$

$$\overline{|\mathcal{M}|}^2 = \frac{8(\epsilon e g_{12})^2 m_T}{\{2m_T(E_2 - E_1) - m_X^2\}^2} \times \left[\mathcal{M}_0(F_1 + \kappa F_2)^2 + \mathcal{M}_1\left\{-(F_1+\kappa F_2)\kappa F_2 + \frac{(\kappa F_2)^2}{4m_T}(E_1 - E_2 + 2m_T)\right\}\right] . \quad (2)$$

$$\mathcal{M}_0 = \left[m_T(E_1^2 + E_2^2) - \frac{(\delta m)^2}{2}(E_2 - E_1 + m_T) + m_T^2(E_2 - E_1) + m_1^2 E_2 - m_2^2 E_1\right] , \quad (3)$$

$$\mathcal{M}_1 = m_T\left[\left\{(E_1 + E_2) - \frac{m_2^2 - m_1^2}{2m_T}\right\}^2 + (E_1 - E_2 + 2m_T)\left\{(E_2 - E_1) - \frac{(\delta m)^2}{2m_T}\right\}\right] , \quad \delta m \equiv m_2 - m_1 \quad (4)$$




- ❑ A large boost factor is **not necessary** to access heavier dark sector states.
- ❑ Cross section is **peaking towards lower energy** proton recoil, while **high energy recoil regime** where DIS becomes relevant is negligible for small $m_X$ (cf. for large $m_X$, the behavior becomes similar to that for neutrino scattering). ⇐ **large momentum transfer suppression** via the dark photon propagator.
- ❑ DIS-induced messy final states mostly come from backgrounds!